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Hydrothermal amphibole in subgreenschist facies mafic rocks, western Sierra Nevada, California

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Abstract

Prehnite-pumpellyite facies metamorphosed volcanic rocks of Jurassic age extend for over 200 kilometers along the western front of the Sierra Nevada of California, and commonly contain the diagnostic assemblage Chl + Ep + Ab + Qtz + Ttn ± Prh ± Pmp. Near the Bear River, the subgreenschist facies rocks also contain amphibole. Based on the field distribution, petrography, and chemical composition of this amphibole, we propose that it was formed during hydrothermal metamorphism associated with the intrusion of small bodies of diabase. Although prehnite and pumpellyite are widespread in the metavolcanic rocks, amphibole is largely concentrated in the vicinity of bodies of metadiabase. The metadiabase commonly contains amphibole in addition to irregular patches of prehnite, pumpellyite and chlorite and euhedral metamorphic quartz. The close association of the amphibole with these patches and its intergrowth with quartz strongly suggest a hydrothermal origin. Amphibole in adjacent prehnite- and pumpellyite-bearing metavolcanic rocks occurs in veins and in aureoles surrounding relict vesicles, suggesting a preference for local environments suitable for infiltration of hydrothermal fluids. The amphiboles in the metadiabases and adjacent metavolcanic rocks have compositions that are similar to those from other known or inferred hydrothermal systems with subgreenschist facies assemblages. They are subcalcic (Ca < 1.9 and Na > 0.1 pfu), aluminous (Si < 7.7, Al > 0.4 pfu), Fe-rich ($Mg/(Mg+Fe^{+2}) < 0.54$), oxidized ($Fe^{+3} > 0.2$ pfu), and/or titaniferous (Ti > 0.02 pfu). In all these respects, they contrast markedly with typical actinolites that coexist with prehnite and pumpellyite in regional and contact metamorphic environments. Subgreenschist facies mafic rocks that contain similar subcalcic amphiboles should be evaluated carefully for independent evidence of hydrothermal processes.

Keywords: amphibole, hydrothermal, metamorphism, prehnite, mafic.

Introduction

During the progressive metamorphism of mafic rocks at low pressure (≤ 3 kbar), the first occurrence of amphibole in the mineral assemblage, Chl + Ep + Ab + Act + Ttn + Qtz, is generally considered to mark the onset of the greenschist facies (e.g. YARDLEY, 1989). However, this assemblage also occurs in subgreenschist facies rocks of appropriate, relatively magnesian compositions (BEIERSDORFER, 1993; BEVINS and ROBINSON, 1993, 1994; BEIERSDORFER and DAY, 1995). In fact, metamorphic amphiboles are quite common in low pressure, subgreenschist facies mafic rocks from different metamorphic environments (LIOU et al., 1987; ROBINSON and MERRIMAN, 1999; ROBINSON and BEVINS, 1999; ALT, 1999). During regional burial or dynamothermal metamorphism within thick sequences of volcanic and sedimentary rocks, metamorphic amphiboles in subgreenschist facies initially occur in mafic rocks at depths of more than 4.5 km (e.g. SMITH et al., 1982; SCHMIDT et al., 1997). They also form during contact metamorphism under similar conditions (e.g. SEKI et al., 1969; CHO and LIOU, 1987; TERABAYASHI, 1993). Less well known, perhaps, is the formation of amphibole by hydrothermal processes in subgreenschist facies rocks within a kilometer of the seafloor (e.g. COISH, 1977; ALT et al., 1985; HARPER et al., 1988).

In this study of subgreenschist facies rocks from the western Sierra Nevada of California, we present field, petrographic, and chemical evidence that amphiboles in metadiabase and in

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nearby metavolcanic rocks were formed by hydrothermal processes. We show that their compositions are distinctly different from the compositions of amphiboles formed in regional and contact metamorphic environments that lack independent evidence for extensive hydrothermal activity. We suggest that rocks containing amphiboles with such compositions should be carefully evaluated for independent evidence of hydrothermal activity.

METAMORPHIC ENVIRONMENTS

Subgreenschist facies mafic rocks form in hydrothermal, regional burial and dynamothermal, and contact metamorphic environments. Hydrothermal metamorphism of mafic rocks is most common in basaltic rocks on the sea floor at or near a spreading ridge (ALT, 1999). Studies of these rocks on land (e.g. COISH, 1977; MUNHA and KERRICH, 1980; SCHIFFMAN and STAUDIGEL, 1994), in dredged samples (e.g. MEVEL, 1981; ITO and ANDERSON, 1983), and by deep sea drilling (e.g. ALT et al., 1985, 1986; LAVERNE et al., 1995) show that amphibole, and mafic mineral assemblages indicative of zeolite, prehnite-pumpellyite, and greenschist facies, occur within one or two kilometers of the sea floor, and are commonly superimposed on one another. The mixed mineral assemblages reflect complex variations of the temperature and composition of the circulating fluids with time and depth as well as the high geothermal gradients, >100 °C/km, characteristic of hydrothermal metamorphism (ALT, 1999).

In comparison, regional and contact metamorphism, without the influence of extensive hydrothermal activity, generally exhibits geothermal

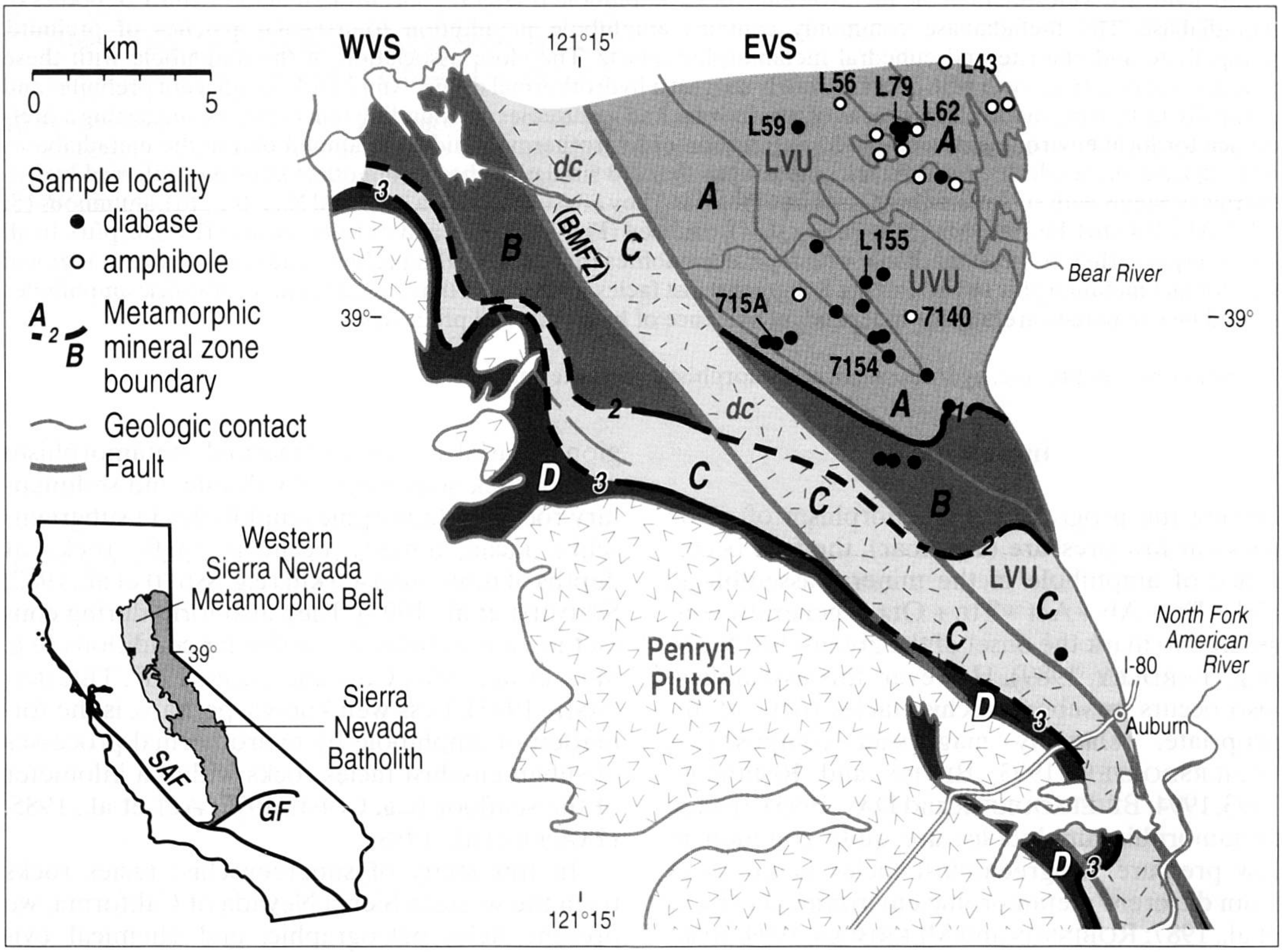

Fig. 1 Metamorphic map of the Bear River Area, Western Sierra Nevada, California. The area of the map is indicated by the small black rectangle in the inset map of California. **Zone A**: Chl + Ep + Ab + Qtz + Ttn ± Prh ± Pmp. **Zone B**: Chl + Ep + Ab + Qtz + Ttn ± Prh ± Act. **Zone C**: Chl + Ep + Ab + Pl + Qtz + Ttn ± Act ± Hbl. **Zone D**: Hbl + Pl ± Ca-Cpx. The dike complex contains assemblages typical of Zone C throughout the area. Abbreviations: dc – dike complex; EVS – eastern volcanic sequence; LVU – lower volcanic unit; UVU – upper volcanic unit; WVS – western volcanic sequence; BMFZ – Bear Mountains fault zone; SAF – San Andreas fault; GAF – Garlock fault.

gradients of <30 °C/km and a relatively systematic progression of mineral assemblages. Many studies have shown that very low to low grade regional metamorphism of mafic rocks at low pressure generally results in a systematic sequence of mineral assemblages such as: a zeolite-bearing assemblage → Chl + Pmp + Prh → Chl + Pmp + Prh + Ep → Chl + Pmp + Prh + Ep + Act → Chl + Prh + Ep + Act → Chl + Ep + Act (SMITH, 1969; LEVI, 1969; BISHOP, 1972; OFFLER et al., 1980; SMITH et al., 1982; NYSTROM, 1983; BEVINS and ROWBOTHAM, 1983; LIOU et al., 1985; LEVI et al., 1989; FREY et al., 1991; BEVINS and ROBINSON, 1993, 1995; POWELL et al., 1993; SCHMIDT, 1993; DIGEL and GHENT, 1994; DIGEL and GORDON, 1995; HIMMELBERG et al., 1995; SCHMIDT et al., 1997; ROBINSON and BEVINS, 1999). The first occurrence of amphibole and the transition from subgreenschist to greenschist facies mineral assemblages within thick sequences of volcanic/sedimentary rocks commonly are > 4.5 km, and > 8 km respectively. Contact metamorphism of subgreenschist facies rocks formed in various metamorphic environments can also result in higher grade, amphibole-bearing assemblages typical of either the subgreenschist or greenschist facies (SEKI et al., 1969; CHO and LIOU, 1987; TERABAYASHI, 1988, 1993)

GEOLOGIC SETTING

The rocks we have studied are part of the western Sierra Nevada metamorphic belt (Fig. 1), which contains a complex transition from Paleozoic continental or near-continental terranes on the east to accreted Jurassic oceanic terranes on the west (e.g. SCHWEICKERT and COWAN, 1975; DAY et al., 1985; SHARP, 1988; DAY, 1992). These rocks were deformed during the late Jurassic "Nevadan orogeny", overlain unconformably on the west by Upper Cretaceous and younger sedimentary rocks of the Great Valley, intruded by the late Cretaceous to early Tertiary Sierra Nevada batholith on the east and south, and covered by Tertiary volcanic and sedimentary rocks on the north and east.

Our study focuses on the Bear River area (Fig. 1), in the youngest, and westernmost terrane of the Western Sierra Nevada Metamorphic Belt. This terrane, named the western belt, is a middle – late Jurassic (c. 160 Ma) volcanic arc, which extends for over 200 kilometers along the western front of the Sierra Nevada of California (e.g. DAY, 1992). North of Auburn (Fig. 1), the western belt is represented by the Smartville complex, a rifted volcanic and plutonic arc terrane (XENOPHONTOS and BOND, 1978; MENZIES et al., 1980; BEARD and DAY, 1987; BEIERSDORFER, 1993), whereas south of Auburn, this belt is largely made up of arc volcanic and hypabyssal rocks overlain by late Jurassic, deformed epiclastic rocks (CLARK, 1964).

THE BEAR RIVER AREA

In the western belt, mafic metavolcanic rocks containing prehnite and pumpellyite are distributed along strike for two hundred kilometers (SPRINGER et al., 1992; BEIERSDORFER and DAY, 1992; SPRINGER and DAY, 1999). In the vicinity of the Bear River (Fig. 1), we recognize an eastern volcanic sequence (EVS) and a western volcanic sequence (WVS) that are separated by a dike complex (dc) composed entirely of metamorphosed mafic dikes. These units were intruded by the granodiorite Penryn pluton, and associated bodies, at about 140 Ma, after the regional metamorphism and most regional deformation. We have defined four regional and contact metamorphic zones in the Bear River area (Fig. 1). Zone A contains the widespread, diagnostic assemblage, Chl + Ep + Ab + Qtz + Ttn ± Prh ± Pmp. This assemblage can be traced intermittently outside the area of Fig. 1, over 70 km to the north (BEIERSDORFER, 1992), and more than 100 km to the south (SPRINGER and DAY, 1999). Zones B, C, and D are clearly related to the intrusion of the Penryn Pluton and will not be considered further here.

The EVS is composed of an upper unit of arc volcaniclastic rocks and lower unit of tholeiitic flow rocks (SPRINGER et al., 1992; XENOPHONTOS, 1984). This sequence has been intruded by dikes and sills of diabase, and, in some cases, prior to the lithification of the volcaniclastic rocks (XENOPHONTOS and BOND, 1978). The metadiabases and adjacent metavolcanic rocks contain the mineral assemblage, Chl + Ep + Ab + Qtz + Ttn ± Prh ± Pmp ± Amp. Metavolcanic rocks that are not associated with metadiabases lack amphibole, but otherwise contain the same assemblage (SPRINGER et al., 1992). Figure 1 illustrates the occurrence of metadiabases in the EVS, and the distribution of amphibole in the metavolcanic rocks. Most of the amphibole in the metavolcanic rocks occurs in the northeastern part of the area, closely associated with metadiabases. The close field association between metadiabases and amphibole in metavolcanic rocks suggests the hypothesis that the amphibole was formed during hydrothermal metamorphism associated with the emplacement of diabasic intrusions. The emplacement of the diabases was probably broadly synchronous with regional Prh-Pmp facies metamorphism (BEIERSDORFER and DAY, 1992; SPRINGER and DAY, 1999).

The WVS (Fig. 1) is composed of a fine epiclastic unit overlying a unit of arc volcaniclastic rocks with minor flows, which correlates with the upper volcanic unit of the EVS (CLARK, 1964; XENOPHONTOS, 1984). In the Bear River area (Fig. 1), the regional metamorphic assemblages apparently have been totally overprinted by the contact aureole of the Penryn Pluton and associated satellite bodies. South of the Penryn Pluton, however, regional metamorphism of the WVS has produced an upper Prh + Pmp zone, and a lower Prh + Pmp + Act zone, both of which are subparallel to stratigraphic contacts. These zones can be traced to the south for about 100 kilometers (SPRINGER and DAY, 1999). Local areas of higher grade may be attributed to buried intrusions, but diabasic intrusions similar to those in the EVS have not been found. Fault offsets of metamorphic isograds suggest that folding, faulting, and associated cleavage formation in the WVS are younger than the regional metamorphism. Consequently, we infer that the WVS has undergone only contact and regional burial metamorphism (SPRINGER and DAY, 1999).

Petrography

INTRUSIVE ROCKS

In the EVS, mafic intrusions occur as dikes, sills, and small bodies of unknown geometry and almost universally exhibit well preserved igneous textures with subhedral, albitized plagioclase, relict igneous Ca-rich clinopyroxene and Fe-Ti oxides. Virtually all are metadiabases and many contain patches of Chl + Ep + Ab + Qtz + Ttn + Prh + Pmp that we infer have been formed through extensive rock-water interaction. Amphibole is commonly associated with such hydrothermal alteration patches (SPRINGER et al., 1992). Pumpellyite, epidote, and prehnite also occur as grains isolated within chlorite patches or grains of albitized plagioclase.

We interpret textural features illustrated in Fig. 2 to indicate that much of the amphibole formed during hydrothermal alteration. Figure 2a shows an example in which amphibole nucleated on relict clinopyroxene and grew into the adjacent alteration patch of pumpellyite, prehnite, and chlorite. Essentially monomineralic patches of prehnite are not uncommon, and Fig. 2b shows an example in which subhedral, tan amphibole has grown in prehnite near a relict Ca-rich clinopyroxene. Amphiboles in the metadiabases also occur as acicular grains radiating from Ca-rich clinopyroxene grains into interstitial chlorite (Fig. 2c), as irregular replacement patches at the edges of or along fractures in Ca-rich clinopyroxene grains, as needles enclosed in irregular patches of chlorite (Fig. 2d). Quartz is not part of the igneous paragenesis, but occurs only associated with the alteration assemblage, sometimes as unusual euhedral grains in patches of chlorite (Fig. 2e). In the same sample (Fig. 2f), subhedral amphibole prisms project into the quartz from relict Ca-rich clinopyroxene.

We infer from these features that the amphibole formed in a hydrothermal environment. Monomineralic veins are commonly interpreted as having formed in the presence of abundant aqueous fluid. In the same way, we suggest that the presence of abundant, essentially monomineralic patches of chlorite, prehnite, or quartz strongly suggests a fluid-dominated alteration. Although quartz and amphibole may form by several common metamorphic reactions, the presence of euhedral quartz and amphibole in otherwise monomineralic patches of chlorite and prehnite is unusual and suggests the presence of abundant fluid. The presence of such euhedral forms is consistent with an easily displaced growth medium, such as a hydrothermal fluid, as is well known in veins, vugs, and amygdules. The simultaneous growth of amphibole and hydrothermal quartz (Figs. 2e–f), and the association of amphibole with alteration patches of quartz, prehnite, chlorite, and the four phase assemblage, Pmp + Prh + Chl + Ep, indicate that the amphibole grew during the same hydrothermal alteration as the patches themselves. Similar alteration patches, as well as euhedral pyroxene and titanite in chlorite veins have been observed in hydrothermally metamorphosed dolerites from Hole 504B (LAVERNE et al., 1995).

Amphibole in the metadiabases exhibits typical pleochroic colors of X = tan, Y = green, and Z = bluish green. In some amphiboles, compositional zoning is shown by bluish green rims on tan cores. Similar textures and optical properties of amphibole have been reported in other subgreenschist mafic intrusives (HENLEY, 1978; MUNHA, 1979; MUNHA and KERRICH, 1980; OFFLER, 1984; LAVERNE et al., 1995).

VOLCANIC ROCKS

Metavolcanic rocks associated with mafic intrusions in the EVS also display petrographic evidence of hydrothermal activity leading to the crystallization of amphibole. In the lower volcanic unit, flow rocks that are intruded by diabase bodies contain monomineralic green amphibole veins

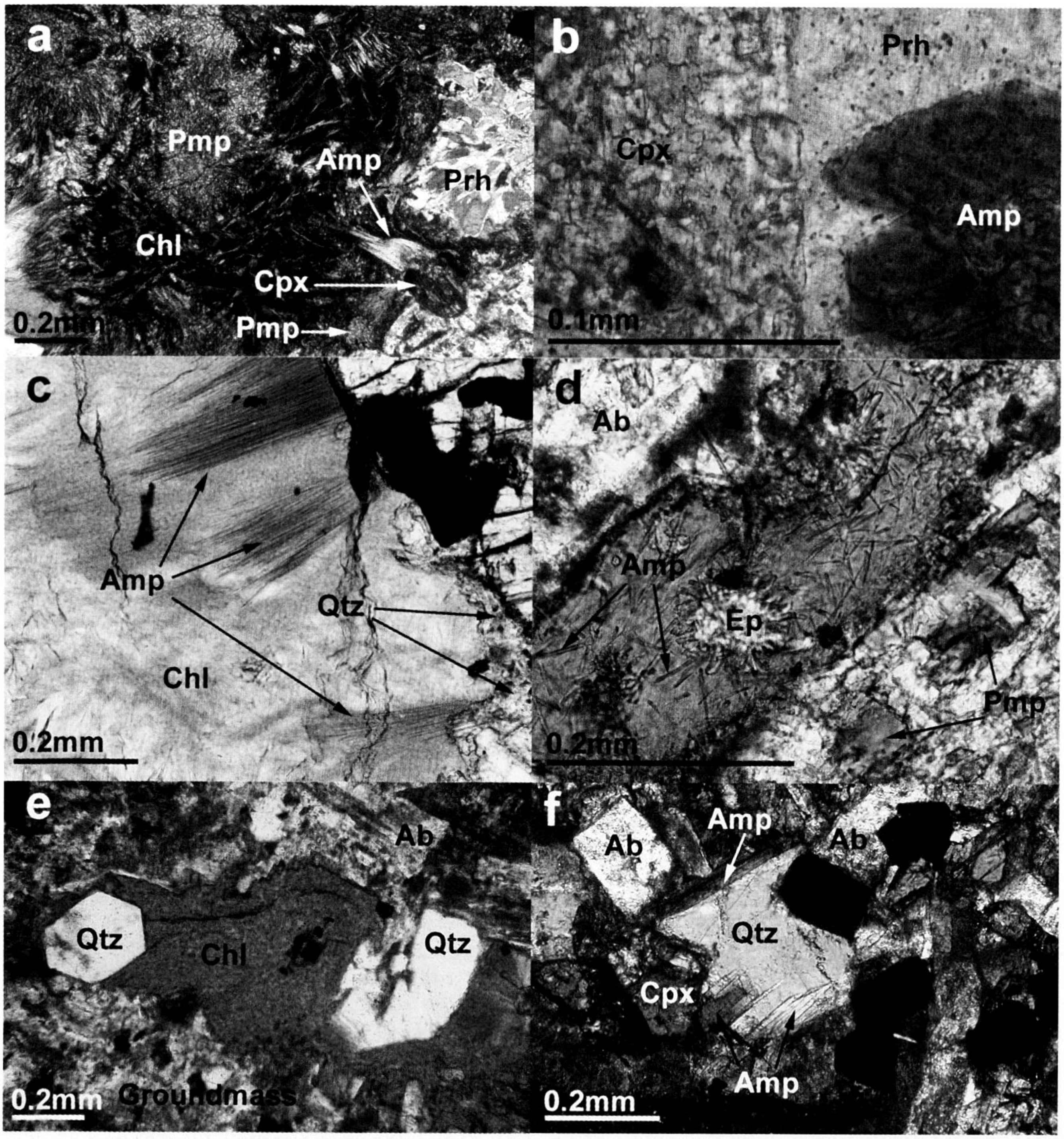

Fig. 2 Textures of metadiabases from the Eastern Volcanic Sequence. Sample locations are given in Fig. 1. (a) Sample 7154. Acicular, tan amphibole radiating from a relict igneous Ca-rich clinopyroxene into an interstitial alteration patch of chlorite, pumpellyite, prehnite, and epidote (not shown). Relict igneous textures are well preserved elsewhere in the thin-section. (b) Sample L59. Euhedral, blue-green amphibole in prehnite alteration patch. Pumpellyite and chlorite are found elsewhere in the thin section. (c) Sample L155. Acicular, bluish green amphibole radiating from a Ca-rich clinopyroxene into an interstitial patch of chlorite, and epidote. Pumpellyite, and prehnite are found elswhere in the thin-section. (d) Sample 715A. Green amphibole needles randomly oriented in chlorite with rosettes of epidote. Adjacent pumpellyite is embedded in albite. Prehnite also occurs elsewhere in interstitial chlorite and albitized plagioclase. (e) Sample L79. Euhedral quartz in alteration patch of chlorite. This sample comes from an area of greenschist facies rocks isolated within the subgreenschist facies rocks. (f) Sample L79. Subhedral, zoned, bluish green amphibole projecting into hydrothermal quartz.

that cut Ca-rich clinopyroxene phenocrysts (Fig. 3a). In other flows, amphibole occurs as radiating bundles of very fine grained, acicular crystals that are restricted to very fine-grained, dark aureoles, only a fraction of a millimeter wide, around amygdules (Fig. 3b). These aureoles may be alteration haloes, or perhaps the rim of segregation vesicles (SMITH, 1967). In either case, the amphibole is found only within a fraction of a millimeter of this original porosity in the rock and not elsewhere in the matrix. An irregular patch of brown amphibole possibly representing the remnants of a similar aureole, is cut by a diffuse vein of pumpellyite and chlorite (Fig. 3c). Elsewhere in the same rock, the assemblage Chl + Ep + Pmp + Prh is abundant. This suggests to us that the amphibole alteration is intimately connected with, but possibly earlier than, the prehnite-pumpellyite assemblage. Euhedral zoned andradite, coexisting with chlorite, epidote, and calcite is present in amygdules of a flow rock within a kilometer of mafic dike outcrops (Fig. 3d) (SPRINGER et al., 1992). Amphiboles similar to those described here have been reported in other subgreenschist facies mafic volcanic rocks (e.g. NYSTROM, 1983; ALT et al., 1986) and similar occurrences of andradite have been attributed to hydrothermal metamorphism (COOMBS et al., 1977; LAVERNE, 1983; SCHIFFMAN and STAUDIGEL, 1994).

Amphibole in volcanic rocks of the EVS appears to be restricted to areas near the intrusive metadiabases. Outside the vicinity of metadiabase intrusions, the metavolcanic rocks in the EVS contain metamorphic textures and mineral assemblages typical of the prehnite-pumpelleyite facies in other regionally metamorphosed sequences of mafic rocks (e.g. BISHOP, 1972; BEVINS and ROWBOTHAM, 1983; BEVINS and ROBINSON, 1993). They are indistinguishable from textures and assemblages in mafic metavolcanic rocks of the prehnite-pumpellyite zone in the WVS.

We have found no independent evidence for hydrothermal metamorphism in the WVS, and we infer that it was affected only by regional metamorphism, and later contact metamorphism by the Penryn pluton. In fact, the occurrence of amphibole in the WVS contrasts markedly with the EVS. South of the area illustrated in Fig. 1, amphibole first appears in rocks containing Pmp + Prh + Chl + Ep as colorless or very pale colored overgrowths on Ca-rich clinopyroxene, and as isolated grains in chlorite (Figs. 3 e–f). Amphibole replacing pyroxene is only observed at the onset of the greenschist facies in these metavolcanic rocks (cf. FAGAN and DAY, 1997). The textures and optical properties of amphibole in the western volcanic sequence are typical of those observed in other subgreenschist facies regional and contact metamorphic terranes (BISHOP, 1972; COOMBS et al., 1976; SMITH et al., 1982; BEVINS and ROWBOTHAM, 1983; BEVINS and MERRIMAN, 1988; TERABAYASHI, 1993).

Mineral Chemistry

AMPHIBOLE

In this section, we compare the compositions of amphiboles from both metadiabases and metavolcanic rocks in the eastern volcanic sequence (EVS) to compositions of amphiboles in other subgreenschist facies mafic rocks. All amphibole analyses were recalculated to estimate the maximum ferric iron according to either 15eK or 13eCNK calculation schemes, on the basis of 23 oxygen ions (LEAKE et al., 1997).

Twelve amphiboles from the EVS that coexist with prehnite or pumpellyite display a wide range of compositions (Fig. 4, filled triangles; SPRINGER et al., 1992; BEIERSDORFER, 1992; SPRINGER and DAY, unpublished). The amphiboles are dominantly magnesiohornblende and ferrohornblende, but also include actinolite, and tschermakite (LEAKE et al., 1997). Iron-rich compositions, containing more than 25 wt% FeO are common. In addition, many analyses are relatively low in calcium, contain significant sodium, and would be classified as barroisite or ferrobarroisite. Amphiboles with abundant ferric iron ($Fe^{+3} > 1.00$ pfu) are common, and the modifiers, ferri- or ferrian, can be applied to many of the calcic and sodic-calcic amphiboles, except for actinolite.

The compositions of amphiboles in the EVS are similar to those of fifteen amphiboles that formed in hydrothermal environments, and coexist with prehnite or pumpellyite (Fig. 4, unfilled triangles). These analyses range from very low in Ca, Na, and Al, i.e. grunerite, to others high in Na and Fe^{+3}, i.e. ferri-ferrobarrosite. Perhaps the best-studied suite of hydrothermally altered mafic rocks from the ocean basins comes from Hole 504B (e.g. ALT et al., 1985; LAVERNE et al., 1995). Amphibole compositions from the EVS and other areas lie in or near the field defined by metamorphic amphibole compositions from mafic rocks in Hole 504B (dashed line, Fig. 4). The field includes ninety-one analyses, dominantly magnesiohornblende, ferrohornblende, and ferri-magnesiohornblende, but also actinolite, ferro-actinolite, and cummingtonite. These rocks were hydrothermally altered within about two km of the seafloor, and commonly contain prehnite, but the exact mineral assemblages in which these metamorphic amphiboles occur are unclear (ALT et al., 1985; LAVERNE et al., 1995). Nevertheless, their compositions correspond well with those known to coexist with prehnite or pumpellyite.

In marked contrast to hydrothermal amphiboles, the compositions of twenty-eight amphiboles coexisting with prehnite ± pumpellyite in

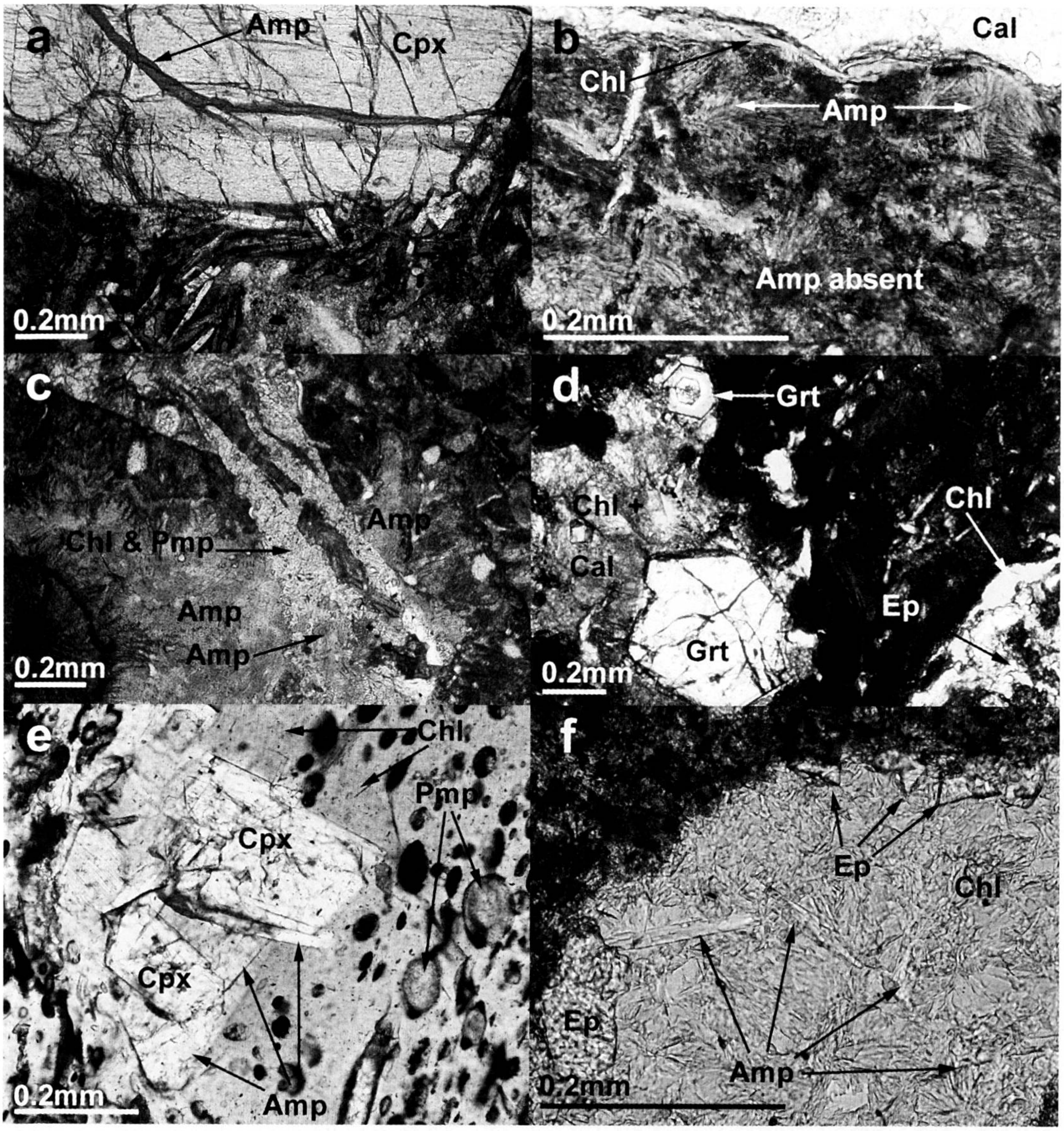

Fig. 3 Textures of metavolcanic rocks from the Eastern (EVS) and Western (WVS) Volcanic Sequences. Sample locations are given in Fig. 1. (a) Sample L62. EVS, flow. Green amphibole vein cutting Ca-rich clinopyroxene phenocryst. (b) Sample L43. EVS, flow. Interlocking, very fine-grained, acicular, green amphibole adjacent to amygdule filled with calcite, prehnite, pumpellyite, epidote, and chlorite. (c) Sample 7140. EVS, flow. Patch of brown amphibole cut by vein of pumpellyite and chlorite. (d) Sample L56. EVS, flow. Zoned garnets associated with chlorite, calcite, epidote, and quartz (no amphibole). (e) Sample SC5. WVS, volcaniclastic, located south of the area shown in Fig. 1. Colorless amphibole growing on Ca-rich clinopyroxene substrate in chlorite matrix with amygdules of pumpellyite (epidote and prehnite not in the field of view). (f) Sample SC34. WVS, volcaniclastic, located south of the area shown in Fig. 1. Isolated needles of amphibole in chlorite amygdule associated with epidote (pumpellyite not in the field of view).

normal contact and regional metamorphic environments show very limited variation (solid line, Fig. 4). The compositions of eight amphiboles from the WVS plot near or within this outlined area (SPRINGER and DAY, unpublished data). According to LEAKE et al. (1997), the compositions of these thirty-six amphiboles are actinolite and ferro-actinolite. Reconnaissance chlorine and flu-

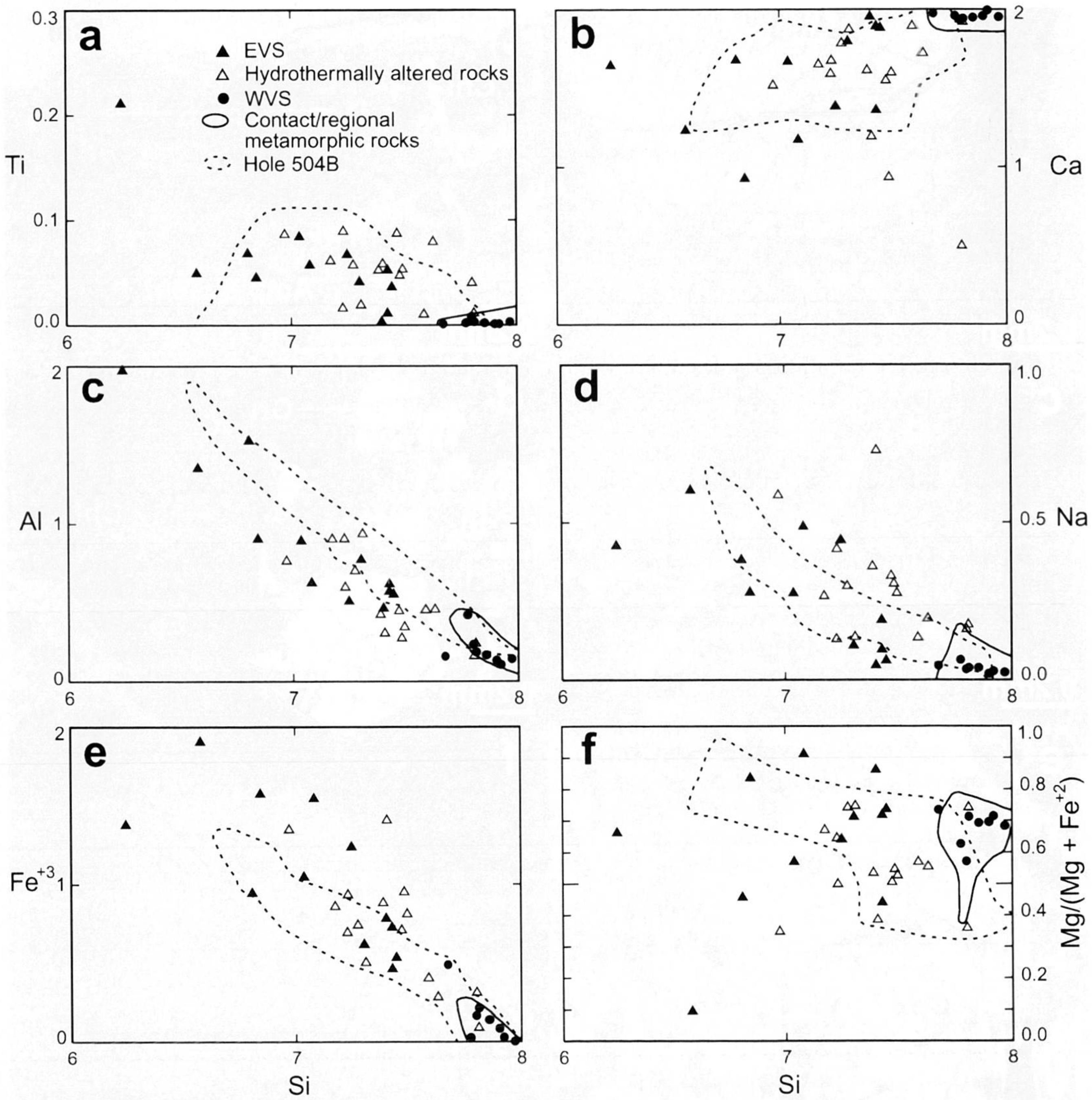

Fig. 4 Composition of metamorphic amphibole in subgreenschist facies mafic rocks. Ti, Ca, Al, Na, Fe^{+3}, and Mg/ ($Mg + Fe^{+2}$) versus Si in amphibole. Symbols: filled triangles – amphibole from the eastern volcanic sequence (EVS) (SPRINGER et al., 1992; BEIERSDORFER, 1992; SPRINGER and DAY, unpublished data), unfilled triangles – amphibole from other hydrothermally altered sequences (MUNHA, 1979; OFFLER, 1984; BEIERSDORFER, 1993), filled circles – amphibole from the western volcanic sequence (WVS) (SPRINGER and DAY, unpublished data), dashed line – area occupied by amphibole analyses from Hole 504B (ALT et al., 1985; LAVERNE et al., 1995); solid line – area occupied by amphibole analyses from typical contact and regional metamorphic terranes (COOMBS et al., 1976; BEVINS and MERRIMAN, 1988; TERABAYASHI, 1988, 1993; BEIERSDORFER, 1993; BEVINS and ROBINSON, 1993; HIMMELBERG et al., 1995; SCHMIDT et al., 1997).

orine microprobe analyses of amphiboles, in the EVS show that amphiboles from four mafic intrusions contain from 0.03–0.99% Cl, and up to 1.07% F. Amphiboles from two volcanic rocks contain up to 0.14% chlorine. These observations might be explained by equilibration with hydrothermal fluids of near seawater salinity (ITO and ANDERSON, 1983; VANKO, 1986; LAVERNE et al., 1995). In contrast, chlorine and fluorine in amphiboles from two volcanic rocks from the WVS, which has not been affected by hydrothermal activity, were below detection limits.

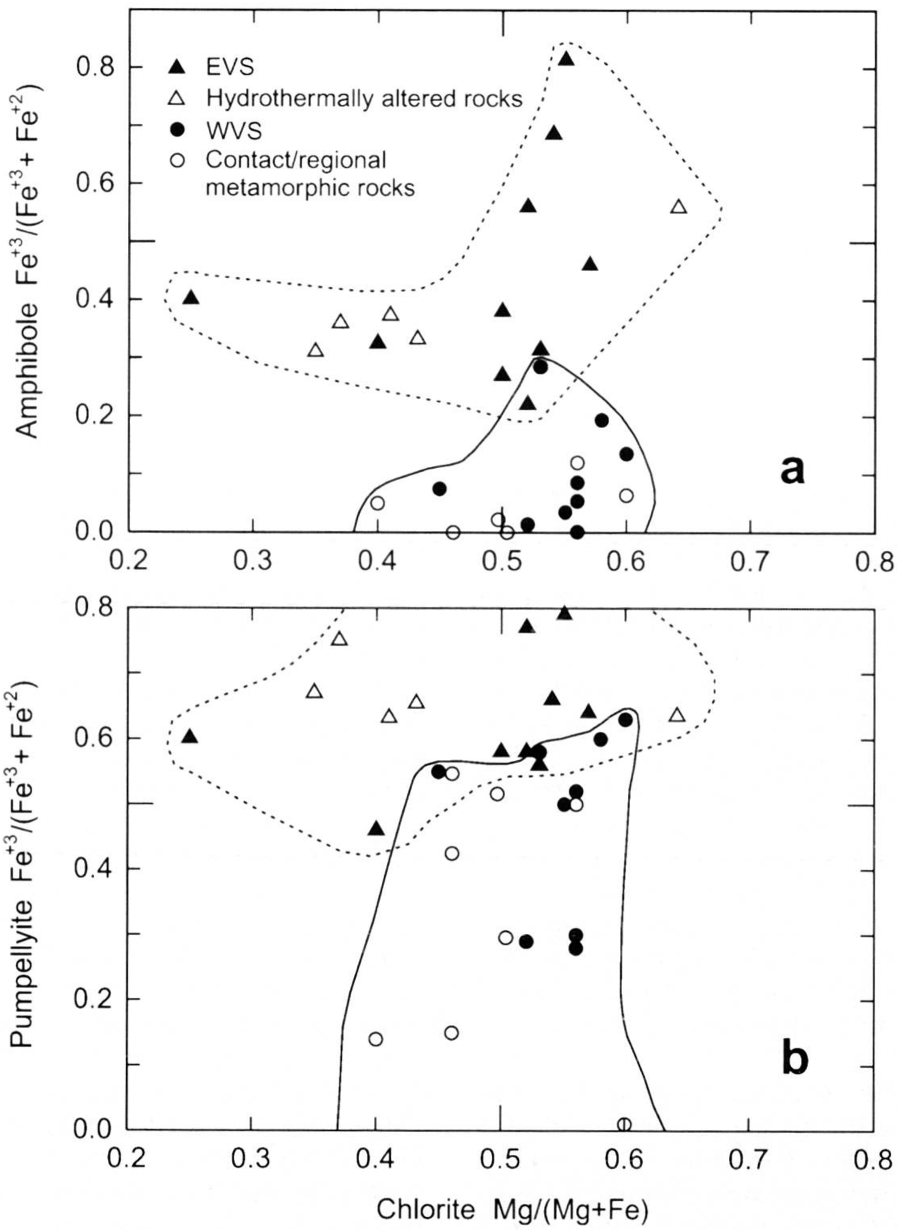

Fig. 5 Composition of minerals in the assemblage, Chl + Pmp + Amp + Ep ± Prh. (a) $Fe^{+3}/(Fe^{+3}+Fe^{+2})$ of amphibole versus Mg/(Mg+Fe) of chlorite. (b) $Fe^{+3}/(Fe^{+3}+Fe^{+2})$ of pumpellyite versus the Mg/(Mg+Fe) of chlorite. Symbols: filled triangles – EVS (SPRINGER et al., 1992; SPRINGER and DAY, unpublished data), unfilled triangles – other hydrothermally altered sequences (OFFLER, et al., 1981; OFFLER, 1984; BEIERSDORFER, 1992, 1993), filled circles – WVS (SPRINGER and DAY, unpublished data), unfilled circles – typical contact/regional metamorphic sequences (COOMBS et al., 1976; TERABAYASHI, 1988, 1993; BEVINS and ROBINSON, 1993; HIMMELBERG et al., 1995).

FERRIC IRON

Figure 5 illustrates the compositions of coexisting amphibole, pumpellyite, and chlorite in very low-grade rocks, most of which contain prehnite. All pumpellyite analyses were recalculated on the basis of 16 cations per 24.5 oxygens (SPRINGER et al., 1992). Both amphibole and pumpellyite in hydrothermally altered rocks from the EVS and other areas have distinctly higher calculated ferric iron than those from contact and regionally metamorphosed environments.

Other calcium silicates exhibit wide ranges in $Fe^{+3}/(Fe^{+3} + Al)$, but are not illustrated here. Epidote coexisting with amphibole in subgreenschist facies mafic rocks, exhibits a range in $Fe^{+3}/(Fe^{+3} + Al)$ from 0.10 to 0.35 (e.g. COOMBS et al., 1976; BEVINS and ROWBOTHAM, 1983; SPRINGER et al., 1992; SCHMIDT et al., 1997). Epidote from hydrothermally metamorphosed mafic rocks plot generally at the Fe-rich end of this range. Although prehnite exhibits a range of $Fe^{+3}/(Fe^{+3} + Al)$ of 0.00 to 0.15, there is no discernible correlation between prehnite composition and metamorphic environment. Andradite, which coexists with the most Fe-rich epidote in the mafic rocks of the EVS, exhibits strong compositional zoning with respect to the Al–Fe^{+3} substitution (SPRINGER et al., 1992). Similar andradite in subgreenschist facies mafic rocks has been attributed to hydrothermal metamorphism (LAVERNE, 1983; SCHIFFMAN and STAUDIGEL, 1994). We have demonstrated no systematic correlations between the Fe^{+3}/(Fe^{+3} + Al) of these calcium silicates and the composition of chlorite or amphibole, at least in part because of the strong variation of Fe^{+3}/(Fe^{+3} + Al) within single grains.

Discussion

Field and petrographic evidence strongly suggests that amphibole in metadiabases and nearby metavolcanic rocks in the eastern volcanic sequence (EVS) formed during hydrothermal activity. The close spatial association of amphibole with the metadiabases strongly suggests that the hydrothermal activity was driven by the diabase intrusions. However, prehnite and pumpellyite are widespread in the EVS (SPRINGER et al., 1992), and it seems likely that the diabase intrusions and hydrothermal activity were broadly synchronous with the subgreenschist facies regional metamorphism. Direct evidence for the relative timing of the regional and hydrothermal metamorphism is sparse.

The petrographic evidence for a hydrothermal origin is supported by the compositions of the amphiboles. Amphiboles coexisting with prehnite and/or pumpellyite from well-characterized regional and contact metamorphic terranes have a very limited range of compositions (Fig. 4). The compositions of hydrothermal amphiboles associated with prehnite and/or pumpellyite from the EVS and other terranes as well as metamorphic amphiboles from Hole 504B display a much wider range of compositions (Fig. 4). In general, hydrothermal amphibole appears to be distinguishable from normal very low grade regional/contact amphibole if the formula unit is sub-calcic (Ca < 1.9; Na> 0.1 pfu), aluminous (Si < 7.7, Al > 0.4 pfu), Fe-rich (Mg/(Mg+Fe^{+2}) < 0.54), oxidized (Fe^{+3} > 0.2 pfu), and/or titaniferous (Ti>0.02 pfu) (Fig. 4).

Hornblendic amphibole compositions are commonly associated with the progressive metamorphism of mafic rocks from greenschist to amphibolite facies, in which metamorphic amphiboles become enriched in Ti, Al, Na, Fe^{+3}, and K with a concomitant decrease in Si, and Ca (ROBINSON et al., 1982). Indeed, we cannot rule out the possibility that some of the hydrothermal amphiboles formed at higher temperatures and were only later overprinted by prehnite- or pumpellyite-bearing mineral assemblages. In the EVS, amphiboles in aureoles surrounding vesicles might have formed prior to filling of the amygdules or veins by low-grade assemblages (Figs. 3 b–c). In the Tal y Fan and Llech Dafad mafic intrusions of Wales, earlier formed hornblendic amphibole, was overprinted by lower temperature, metamorphic mineral assemblages containing actinolite (BEVINS and ROBINSON, 1993). Although some hydrothermal amphiboles may have formed at higher temperatures, the petrographic evidence is clear that most are closely associated with low pressure, subgreenschist facies assemblages. In addition, the analyses of amphiboles from prehnite-pumpellyite facies mafic rocks illustrated in Fig. 4 imply a restricted range of low pressures and temperatures (FREY et al., 1991, SCHIFFMAN and DAY, 1999).

We have no reason to suppose that the unusual compositions of the low-grade hydrothermal amphiboles are an effect of unusual bulk rock compositions. The mafic rocks are broadly similar in composition, and contain very similar igneous and metamorphic mineral assemblages. The metamorphic assemblages are systematically disposed in composition space as required by the phase rule, such that variations in the abundances of alkali elements, aluminum, calcium, iron, and magnesium should change only modal abundances of minerals in the assemblages (SPRINGER et al., 1992; BEIERSDORFER and DAY, 1995). The Mg/(Mg+Fe^{+2}) of chlorites in hydrothermal and regional/contact metamorphism are broadly similar, suggesting that bulk Mg/(Mg+Fe^{+2}) was similar in these rocks (Fig. 5). Some differences in physical conditions seem required in order to explain the contrasting compositions of hydrothermal and regional/contact amphiboles.

The composition and oxygen fugacity of the fluid phase may help account for the unusual amphibole compositions observed in subgreenschist facies hydrothermal metamorphism. For example, iron-rich, sub-calcic amphiboles, containing up to 37 wt% FeO, 1.0 wt% Cl, and 2.0 wt% Na_2O, are found in the EVS (SPRINGER et al., 1992; this study). During hydrothermal metamorphism, circulating fluid, initially near seawater composition, may evolve into highly saline brines by phase separation at shallow levels (≤ 3 km) near the seafloor (SEYFRIED and DING, 1995; VON DAMM, 1995). Sodium and iron are highly soluble in such brines, which apparently stabilize sodium and iron-rich minerals. In fact, riebeckite and arfvedsonite have been documented in hydrothermally altered mafic rocks near the sea floor (HENLEY, 1978; MUNHA, 1979; MUNHA and KERRICH, 1980). Oxidizing conditions during shallow, hydrothermal metamorphism may also contribute to the unusual compositions. The high $Fe^{+3}/(Fe^{+3}+Fe^{+2})$ values of amphiboles and pumpellyite, and the presence of Fe-rich epidote, and andradite in the EVS are consistent with higher oxygen fugacity at shallow levels (ALT, 1999). The high iron content (> 25 wt% FeO) in some amphiboles from Hole 504B has been attributed to fluid composition (LAVERNE et al., 1995) and similar Fe-rich chlorite and epidote are observed in hydrothermal upflow zones (SHIKAZONO and KAWAHATA, 1987; ZIERENBERG et al., 1988; HARPER, 1995).

Amphiboles formed during very low grade regional metamorphism of mafic rocks are typical actinolites, i.e. low Na, Al, Ti, Fe^{+3}, and high Si and Ca. Mafic rocks in the WVS, where there is no independent evidence of hydrothermal metamorphism, contains such typical actinolites. At deeper levels of a volcanic arc sequence (> 5 km?) where these rocks may have formed, fluid/rock ratios are expected to be much lower than near the seafloor. Furthermore, the fluids would be much less saline because phase separation would not take place at these depths (VON DAMM, 1995), and metamorphic dehydration reactions would flush the fluid phase with nearly pure H_2O. Consequently, at deep levels in volcanic/sedimentary sequences, the fluid phase is likely to be less saline and less oxidizing, so that unusual compositions of the amphibole may not be stable. In agreement with this view, MUNHA and KERRICH (1980) interpreted the replacement of riebeckite by actinolite as an effect of decreasing oxygen fugacity and Na activity in the fluid phase with progressive metamorphism.

A major premise of our discussion has been that "hydrothermal" metamorphism can be distinguished from "normal" "contact" or "regional" metamorphism. In practice, of course, unambiguous distinctions are difficult to make because the physical, chemical, and spatial parameters that characterize these end-member concepts are completely and continuously gradational. Pressures, temperatures, fluid compositions, fluid/rock ratios, and both rates and scale of fluid migration vary continuously from one of these metamorphic regimes to the other. Many of the features we have described in the altered diabases might be considered "deuteric". Likewise, the formation of low calcium amphibole in the adjacent volcanic rocks due to heat and fluids near the contacts of the diabases might be considered "contact" metamorphism. Regardless of the name we attach to the processes, significant infiltration of fluids at elevated temperatures seems to be required.

Conclusions

In prehnite-pumpellyite facies regional and contact metamorphic environments lacking evidence for extensive hydrothermal metamorphism, colorless or pale green metamorphic amphiboles, occur as "whisker" overgrowths on relict igneous pyroxenes, or as isolated grains enclosed in interstitial chlorite. The compositions of these amphiboles are most commonly actinolites with formula units that are calcic (Ca > 1.9, Na < 0.1 pfu), silicic (Si > 7.7, Al < 0.4 pfu), magnesian ($Mg/(Mg+Fe^{+2})$ > 0.54), low in ferric iron and titanium (Fe^{+3} < 0.2, and Ti < 0.01 pfu).

Subcalcic, iron-rich amphiboles coexisting with prehnite or pumpellyite in the eastern volcanic sequence are not typical of subgreenschist facies regional/contact metamorphism of mafic rocks. The field setting and petrographic evidence suggest that these unusual amphiboles were formed during shallow, hydrothermal metamorphism associated with the intrusion of diabases into volcanic rocks at prehnite-pumpellyite facies conditions. The hydrothermal amphiboles, which commonly replace igneous pyroxenes, display a wide range of pale green, blue green, and tan pleochroic colors. The compositions of these amphiboles (magnesiohornblende, ferrohornblende, tschermakite, barroisite, and ferrobarroisite) are similar to those in other prehnite- and/or pumpellyite-bearing terranes for which a hydrothermal history can reasonably be inferred. Hydrothermal amphibole can be distinguished from more typical very low-grade regional/contact amphibole on the basis of composition if the formula unit is subcalcic (Ca < 1.9; Na > 0.1 pfu), aluminous (Si < 7.7, Al > 0.4 pfu), Fe-rich ($Mg/(Mg+Fe^{+2})$ < 0.54), oxidized (Fe^{+3} > 0.2 pfu), and/or titaniferous (Ti > 0.02 pfu). Very low-grade mafic rocks that contain amphiboles with such compositions should be carefully evaluated for independent evidence of hydrothermal activity.

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